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Particle hydrodynamics of the electrical discharge machining process. Part 1: Physical considerations and wire EDM process improvement

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Abstract

During these last years, the evolution of the machining speed of the EDM processes has become a key challenge for this technology. The recent progress made on the spark generators leads to a higher production speed in all processes such wire EDM, die-sinking, drilling, milling, etc. Nevertheless, if the electrical process is developing fast, many limiting factors still remain under investigations. In this context, our group started 7 years ago a research program to increase the understanding of the EDM particle hydrodynamics. We describe in this paper some results obtained and discuss the physical aspects related to the evacuation of the machining debris.

During the EDM process, if the cleaning of the dielectric is not effective and some debris remain in the gap, the electrical resistance is locally reduced and the spark occurs at the same place. The process cannot go farther. In this situation, i.e. when the spark frequency and power are high enough, the machining speed is governed mainly by hydrodynamics. In this paper we will present efficient strategies to clean the gap in the wire EDM (part 1) and die sinking processes (part 2).

For the wire EDM process (part 1), we have designed and analysed dielectric injection nozzles with the aim of improving the cleaning processes in the gap. Three main tools have been used to achieve this goal. The first is a fluid flow simulation model using CFD solvers. Then, the results have been validated using experimental techniques at full scale on EDM machines. Finally, a test rig has been developed and experimental analyses have been done.

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Keywords: Wire EDM; WEDM; particles; cleaning; hydrodynamics; CFD; experiments

1. Introduction

In the EDM process (Fig. 1), the plasma generated during the heating phase leads to the presence of liquid material and gas. When the plasma disappears, a pressure wave is generated that move the melted material in the dielectric. Solid particles are formed (Fig. 2). A crater is formed; this is the machining action (Fig. 3). The particles remain in the dielectric closed to the crater (Fig. 4). These have a spherical shape and move in the liquid. The density of these is higher than the liquid, then the trajectories of the debris are not directly which of the fluid particles. They need to be observed or calculated, according to the laws of the motion of a high density solid in a fluid flow. The forces are the hydrodynamic force, the hydrostatic force (Archimedes' force) and the mass forces (gravity and acceleration).

The EDM process needs some impurities in the dielectric liquid. If these are not present sparks cannot be generated. At the other hands, if the impurities are in big quantities and located at the same place, the spark will be produced always at the same place. This is due to the fact the particles decrease the resistance of the dielectric.

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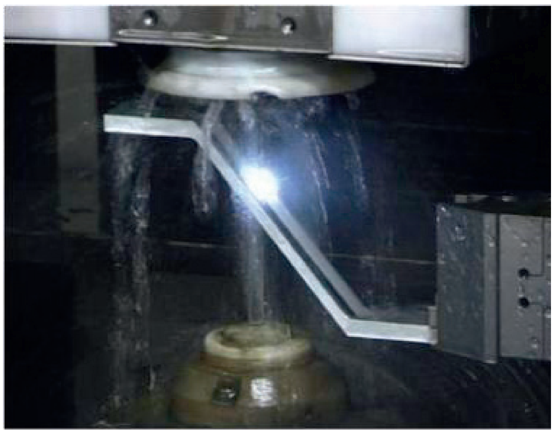

Fig. 1: Wire EDM production of a complex part.

The spark will not move and will try to remove material always at the same place. The machining process will not work properly. The objective of the project is to understand what is a good cleaning of the gap and how to obtain it.

2. Project approach

The project is based on three approaches. Machining tests were performed at the beginning and all along the project. Also, technicians having a great experience regarding the EDM process have followed the project and commented the analyses. Machining tests are very helpful to confirm the conclusions but don't give the possibility to understand the process and the fluid flow behaviour in the nozzle and in the part. For this reason, we built a test rig with an instrumented nozzle. Finally, we decided to develop CFD models and benefit from high performance simulation technics. This last approach, after a validation phase, gave us the possibility to visualize the flow inside the part and the nozzle in a very efficient way. The flows obtained with several prototypes of nozzle have been described and their cleaning performances have been evaluated.

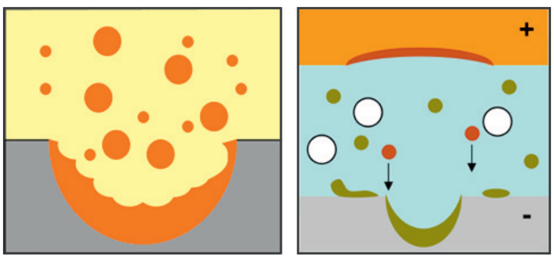

Fig. 2: *Particle generation process.*

3. Theoretical design and machining tests

The great experience of the industrial partner of the project is the starting point. It appears immediately the flexibility of the nozzles designed is generally important. Some specific designs can be implemented to obtain high particle cleaning efficiencies, but these give limiting application flexibility.

$$\frac{c^2}{2} + \frac{p}{\rho} + gdz = 0 \qquad (1)$$

$$c = \sqrt{\frac{2}{\rho}(p_0 - p)} \qquad (2)$$

The research group first designed nozzles based on a theoretical approach. This approach was to ensure the static pressure at the nozzle outlet is equal to the pressure existing in the dielectric tank closed to this point. In this nozzle, the upstream pressure energy is completely transformed in kinetic energy at the outlet. In this case the nozzle is called "adapted". The speed of the jet at the outlet is the maximal reachable. This can be called a "dynamic pressure nozzle". The law governing the transformation of the energy is given by equations 1 and 2, and represented in figure 5. This is a simple law based on Bernoulli equation. This approach is really known by hydrodynamic engineers and the work appears to be easy.

In practice, machining tests and the technician experience show this is difficult to work with such nozzles. The results we got confirm that. When the part to be machined is not there, the jet is straight and everything seems to work fine. A strong jet is present. However, when we are in machining conditions, the jet is modified by the presence of the part, and the flow cannot be considered ending in a infinite space. The expected result is not reached.

The cleaning effect is not bad, but the jet speed is high and the wire vibrates. The flow generates instabilities at the slot entrance that propagate in the gap. Practically, it was difficult to work with such dynamic

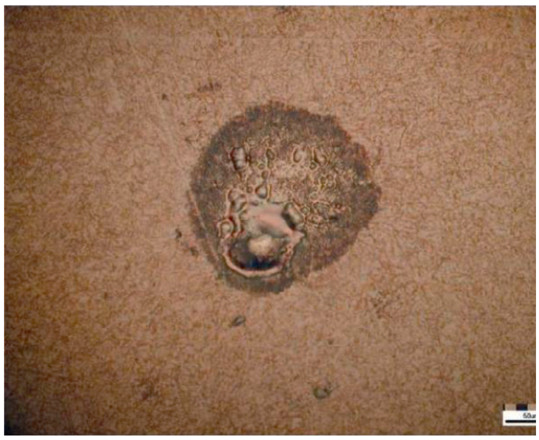

Fig. 3: View of a crater produced at the surface by the spark. Melted material can be seen [2].

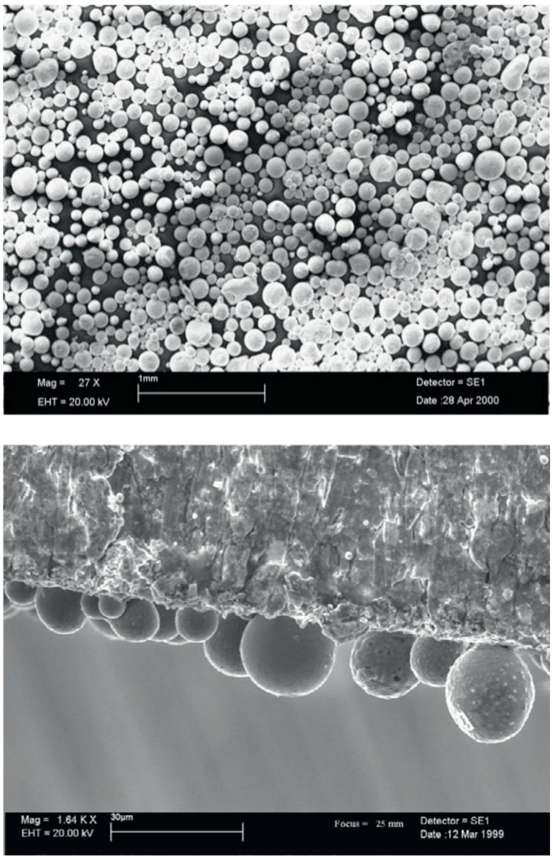

Fig. 4: Closed view of the particles generated during the EDM process. The diameter of the particles is about 10 microns. In the EDM processes, the particles diameter can be much bigger [2].

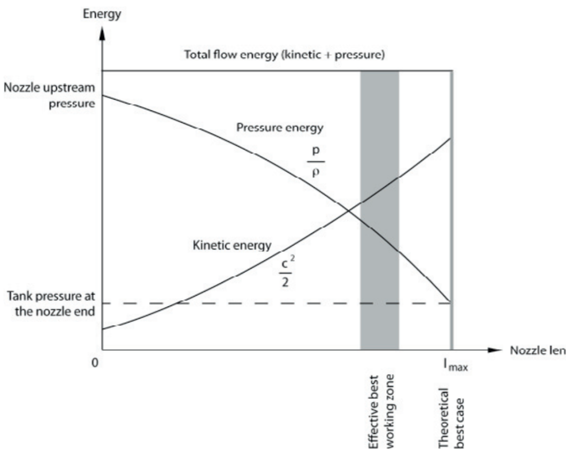

Fig. 5: Energy transformation process in the nozzle.

pressure nozzle.

The nozzles were then modified to work with a part of static pressure. In this case, the gap between the part upper surface and the nozzle shall be small to ensure static pressure at the slot entrance. Hybrid design nozzles have been produced working with static and dynamic pressure. In figure 5 this nozzle is located in the "effective best working zone".

4. Hydrodynamic study on test rig

A part and a nozzle have been instrumented using 35 pressure sensor tabs (Fig. 6). The part height is 50 mm and the slot is 0.35 mm width. It includes a wire of 0.25 mm diameter. The effective gap was then 0.050 mm. The system was installed on a ROBOFIL 330 WEDM machine from AgieCharmilles SA. The system simulates a real tooling process from the fluid dynamics point of view. All electrical functions were not used, but the liquid was injected as during a true machining process. The pressure has been measured in the slot and in the nozzle upstream for several machining situations.

The first result obtained was the discovery of an annular vortex located between the nozzle and the upper surface of the part (Fig. 8). These nozzle annular vortices are stable and their existence depends of the height of the nozzle and the speed of the jet.

Other typical results we obtained are the pressure

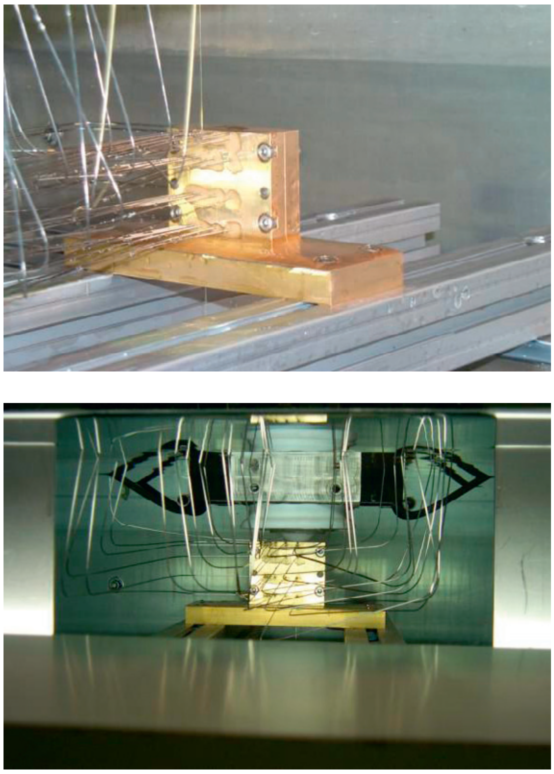

Fig. 6: Hydrodynamic test model (a) and test set-up (b). In picture (a), we can see the wire passing through the part vertically.

measurements on the slot sides and front (Fig. 7). In Fig. 9, each curve represents a location from the end of the slot. The “g” curve shows the measurements at the front of the slot.

The flow takes 2 – 3 mm to stabilize in the gap. Then, the flow speed reduces slowly and the pressure becomes low. After 12 mm, the pressure is 50% of the minimum value obtained at 2 mm (point of higher speed in the gap). After 30 mm, this value becomes 10%. We can see the effect of the jet is high over 30 mm height. In this region the cooling and cleaning effects are very high. For a distance from the surface bigger than this value, the effect of the jet is considerably reduced.

Some other tests with a part of 100 mm height were also performed. The conclusions about the pressure field are the same as for the tests with a 50 mm height part.

Table 1. Dielectric characteristics (40 °C)

Dielectric	Density (kg/m3)	Viscosity (*kg/ms*)
Water	998	0.001003
Dielektrikum OH 2286	770	0.001078
Ionoplus IME-MH	790	0.001975

5. CFD study results

The CFD study has been made using several mesh types. First, tetrahedrons have been used to produce a mesh in a short time (Fig. 10). The geometry is really complex and includes a very small slot at the same time than large volumes. The first results obtained with this unstructured approach show a much higher spatial resolution must be obtained to give an acceptable accuracy. To achieve this, a more sophisticated mesh has been produced using about 2 millions of hexahedrons. The size functions controlling the growing rate of the cell size give the possibility to pass from cells of 0.005 mm in the gap to about 20 mm in the far from the

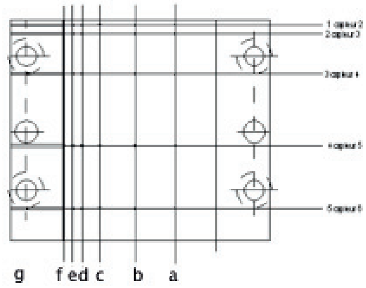

Fig. 7: Hydrodynamic test model and pressure tab references.

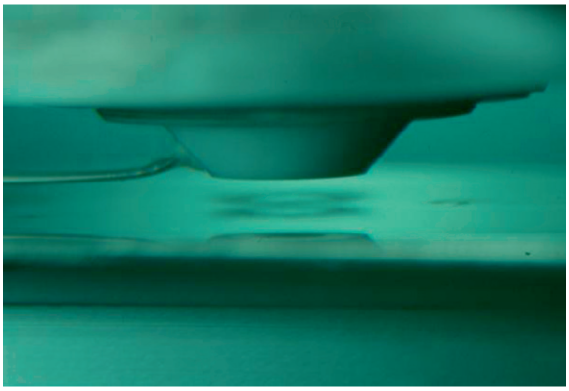

Fig. 8: Located under the injection nozzle at the center of the picture, we can see the nozzle annular vortex.

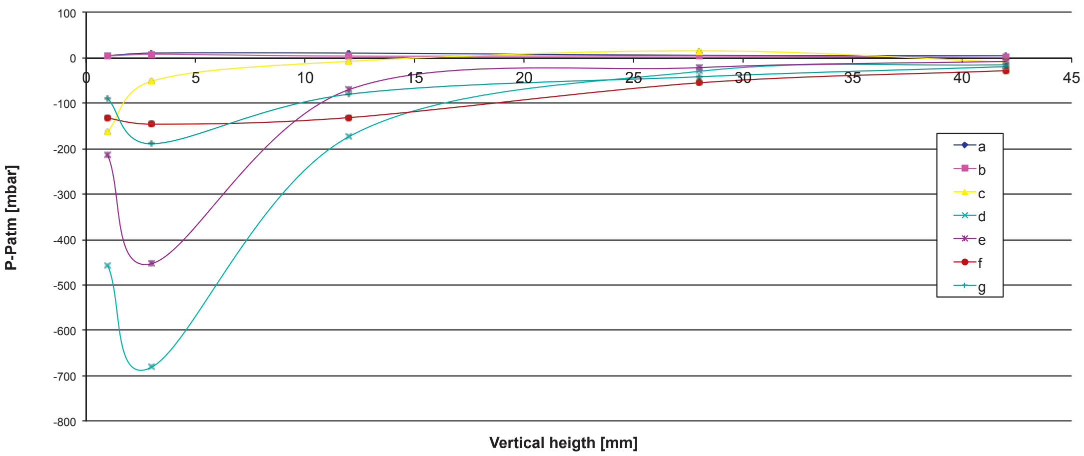

Fig. 9: Example of hydrodynamic test measurements. Pressure measured in the slot at several locations (according to Fig. 7) and heights from the part surface.

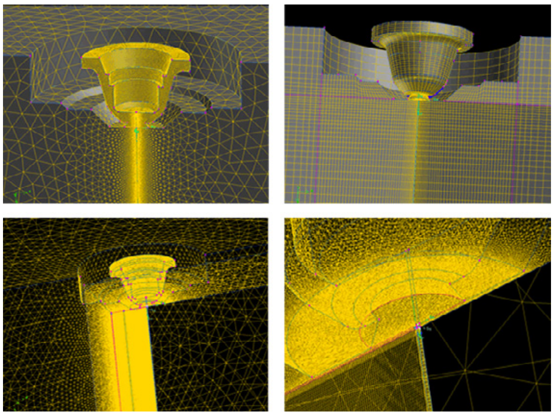

Fig. 10: Two types of meshes used for the CFD study: hexahedrons and tetrahedrons. Upper: without part, lower: with part and slot.

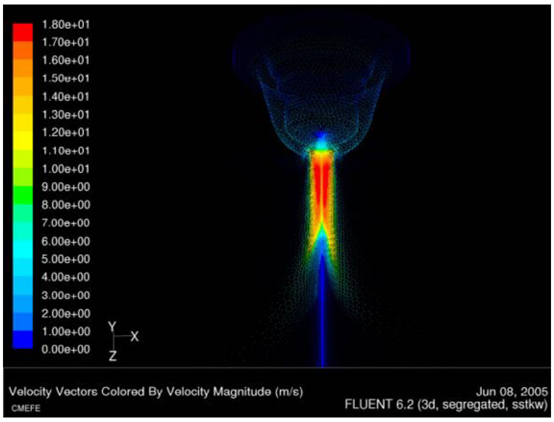

Fig. 11: Dielectric jet without the part. Velocity vectors colored by velocity magnitude in m/s.

process in the dielectric tank. A so high growth on a distance of about 0.2 m was difficult to achieve. It leads with the geometry of the cells and their qualities for numerical calculations (skewness).

The CFD algorithm used is the semi-implicit for pressure linked equations (SIMPLE) algorithm implemented in the commercially available software FLUENT. The spatial interpolations are of second order and the fluid is assumed to be of constant density. The characteristics of the fluid used for the study are summarized in table 1.

The turbulence model is a $\kappa-\omega$ SST with low Reynolds number correction from Menter [5]. The distribution of the height of cells along the walls, expressed in term of sub-layer thickness y^{+} was in the range of 4.0 to 7.0. This result was difficult to achieve in regards of the complexity of the geometry. Even a value a little lower should normally be obtained according to the author of the turbulence model, this mesh has been used for the study. Values lower than 5 shall normally be target.

The results obtained with the CFD are typically the field of velocities and static pressures. The jet generated by the nozzle is annular, due to the presence of the wire at the center. Several analyses without the part to be machined have been done to validate the CFD model in much simple situations as a first step (Fig. 11). Then, real situations with the part have been simulated (Fig. 12 and 13).

The CFD results give us a good understanding of the flow behavior in the gap and in the slot on the backside of the wire. The following aspects have been studied with the CFD model:

- Particles cleaning efficiency (interpreted as the magnitude of speed in the gap)
- Wire cooling effect (activating the energy equation in the model and evaluating the thermal fluxes at the wire wall)
- Wire stability (from a discussion of the flow induced excitations obtained in unsteady mode)

The model has been validated based on results obtained with the hydrodynamic test rig. Then, it has been used to propose improvements of the nozzle designs. Theses recommendations concern:

- The section at the end of the nozzle
- The shape of the final part
- The angles and radii inside the nozzle

Generally, a correlation inside 15% of accuracy has been achieved between the CFD and the experiments on the pressure field (relative pressure). More than exact quantities, the CFD gives us a very good understanding of what append in the nozzle and the gap.

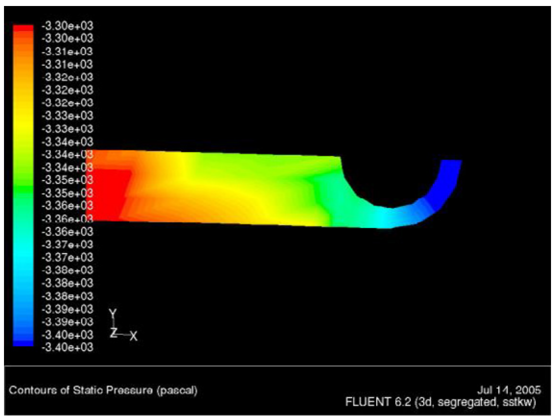

Fig. 12: Dielectric jet in machining conditions. Static pressure distribution in pascals in a plan located at 10 mm from surface. The wire diameter is 0.25 mm and the gap 0.050 mm.

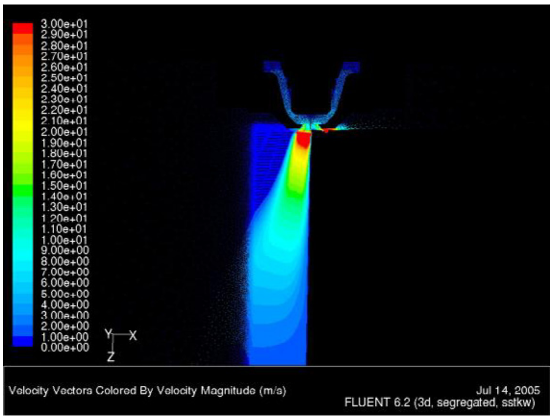

Fig. 13: Dielectric jet in machining conditions. Velocity vectors colored by velocity magnitude in m/s.

Fig. 14: Rapid prototyping nozzle used for tests.

Conclusion

Based on the experimental and CFD analyses presented here, new nozzles have been proposed. Some have been produced using rapid prototyping technics (Fig. 14). This offers a fast way to the test campaign. The mechanical resistance of them is much inferior to the original ones and some simple modifications were necessary to ensure their use in normal conditions of pressure.

The nozzles were tested first on the “test rig”, and then in real conditions on a wire-EDM machine. The increases in production speeds have been recorded for specific situations, more of all on parts of high thickness. This last situation is critical and leads to very low production speeds. According to Fig. 9, the flow in the center of the part is very reduced and the wire is not cooled enough. The wire breaks easily if a fast production regime is settled.

Generally, the new nozzle designs can offer increases in cooling effect of about 20%, depending on the original one and the situation.

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